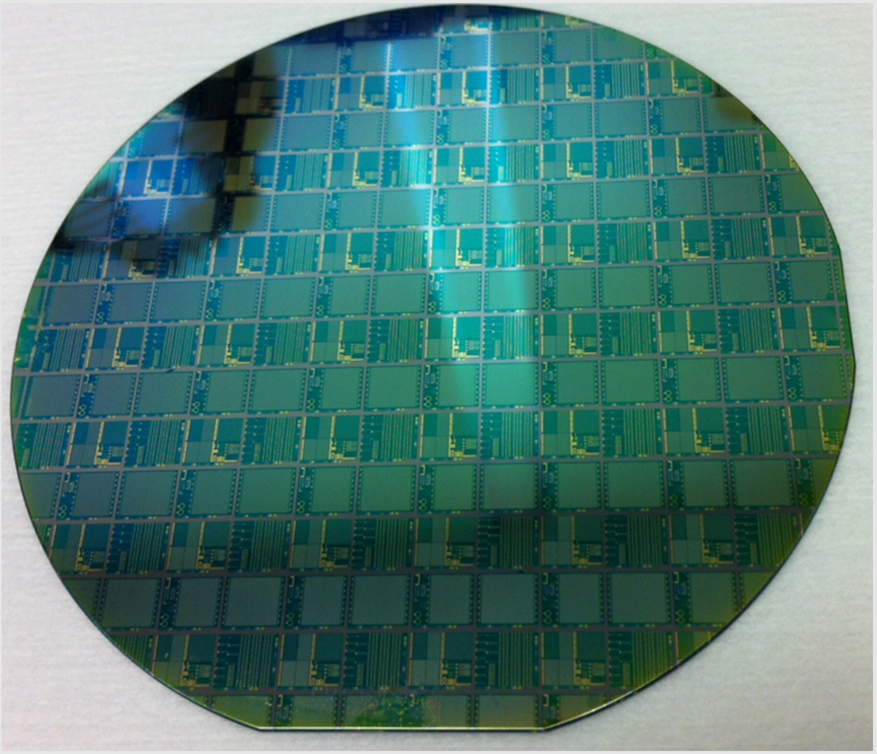
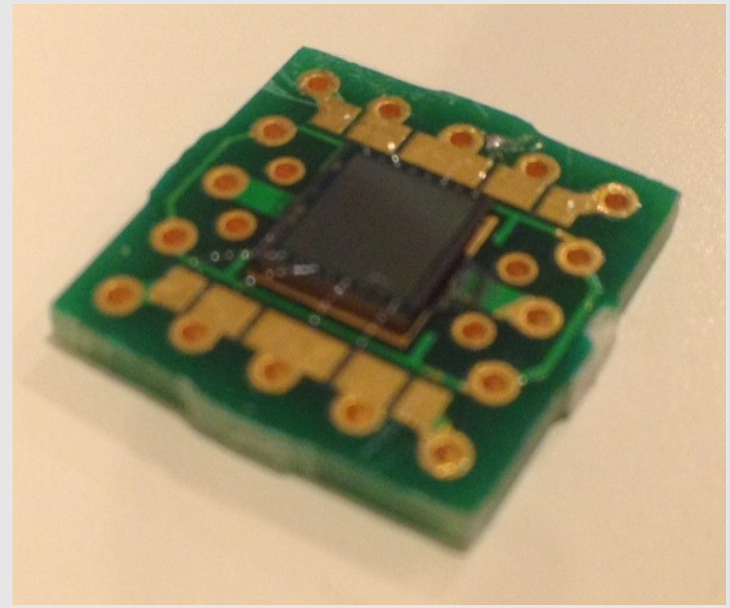
Studies of GaInP based SPAD arrays





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Studies of GaInP based SPAD arrays

Demands are likely to increase for radiation and B-field tolerant technologies for visible light detection in High Energy Physics and related fields.

Silicon based SPAD arrays (SIPM) have been highly optimized to achieve impressive performance in terms of
noise / detection efficiency at room temperature.

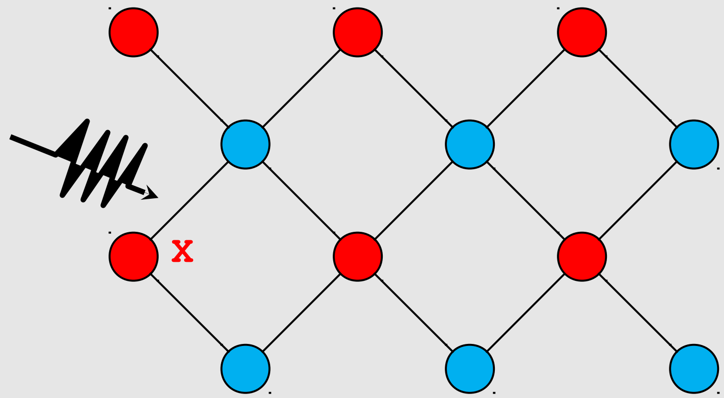
Challenges remain to preserving this high figure of merit in collider environments with large integrated particle flux incident upon the detector elements.

This talk summarizes
- Motivation for exploring compound semiconductors, specifically GaInP
- Initial studies of new GaInP SPAD arrays

Work in progress

Why GaInP for rad hard devices?

Bulk defects: intrinsic materials property, accurate measurements.



Induced generation rate:

$$G(\Phi) = n_i / \tau_{SRH(\Phi)}$$
$$= n_i \times (K \times \Phi) \times (\text{Area} \times W)$$

	n_i	K	G (Φ) cps/mm²
Silicon	1E10/cm³	0.10E-6 cm²/s	1.0E-3 × Φ
GaAs	2E6/cm³	1.25E-6 cm²/s	2.5E-6 × Φ
GaInP	300/cm³	1.25E-6 cm²/s	3.8E-10 × Φ

- n_i : intrinsic carrier concentration
- K: lifetime radiation damage factor
- Φ: radiation flux
- W: thickness of active region (~1um)

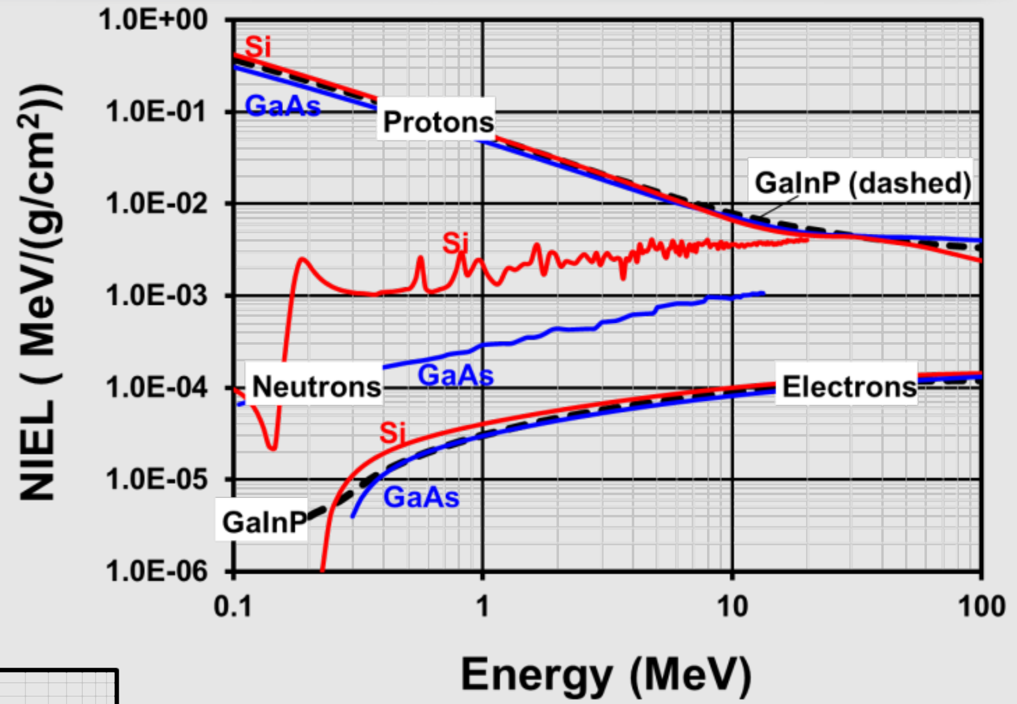
Intrinsically rad-hard material

But, also have surface defects: depend on surface treatment

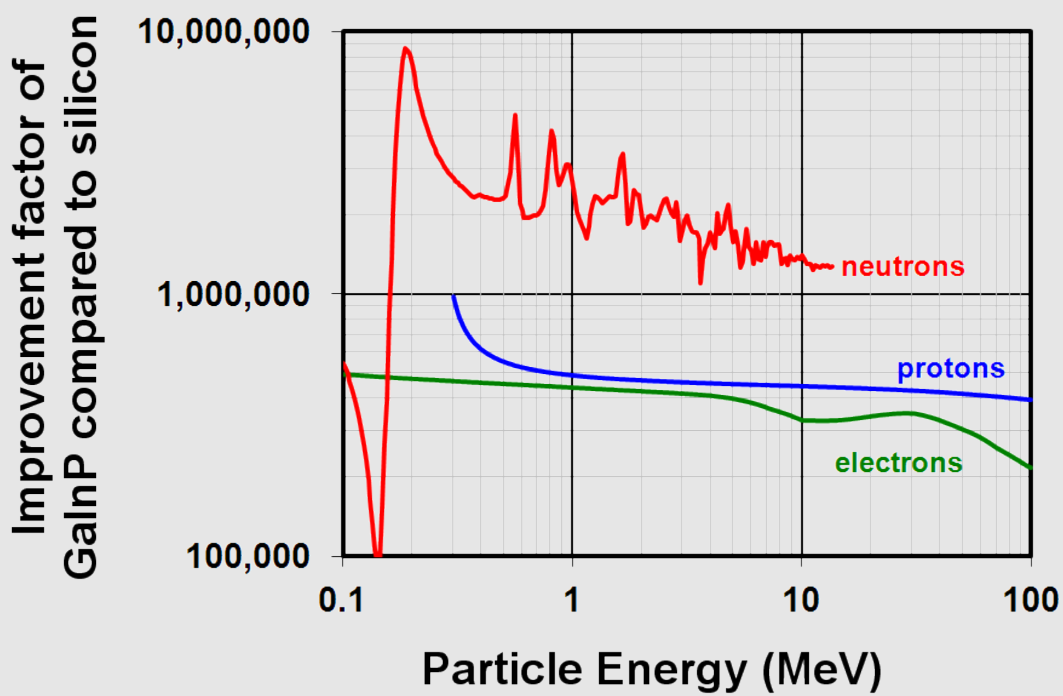
- Si: SiO_2 vs. Si_3N_4
- GaAs, GaInP
  - Surface passivation: imperfect dielectric vs. perfect single-crystal, etc

=> engineering+physics problem

NEIL and relative G(Φ)



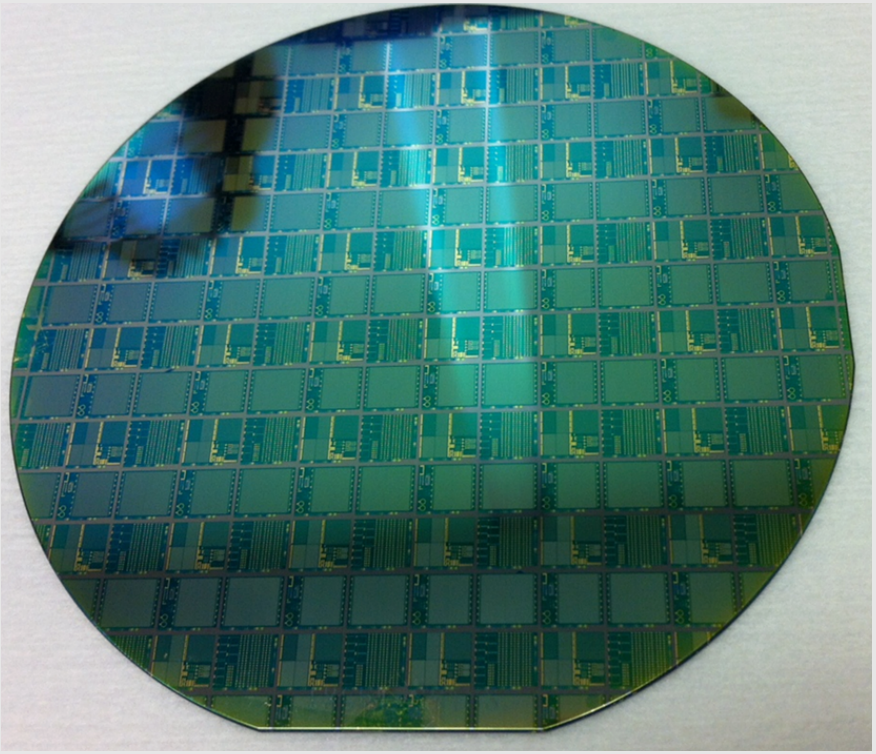
Expectations for relative improvement in radiation-induced bulk damage effects for GaInP



Practical:
building devices / tuning designs required!

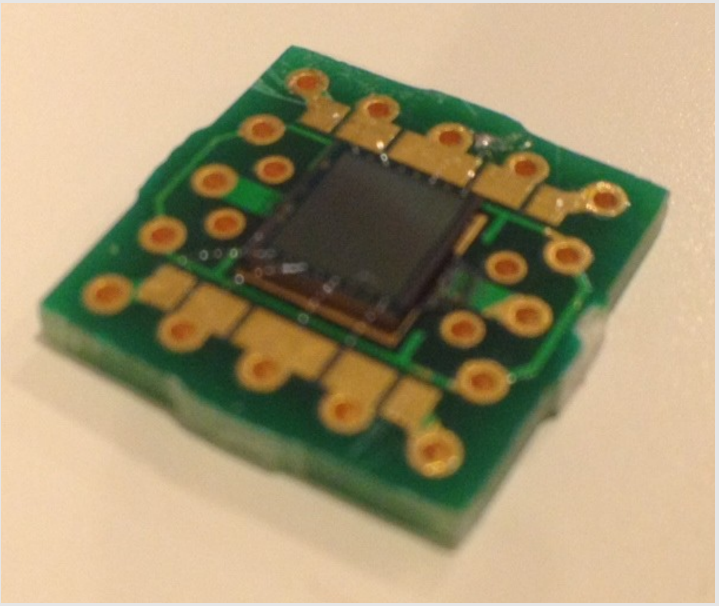
Test devices in this talk

GaInP Photomultiplier Chips™



75 mm wafer

1.0x1.5mm arrays
2400 x 25u SPADs



4 mm x 4 mm PMC™

LightSpin Technologies, Inc.

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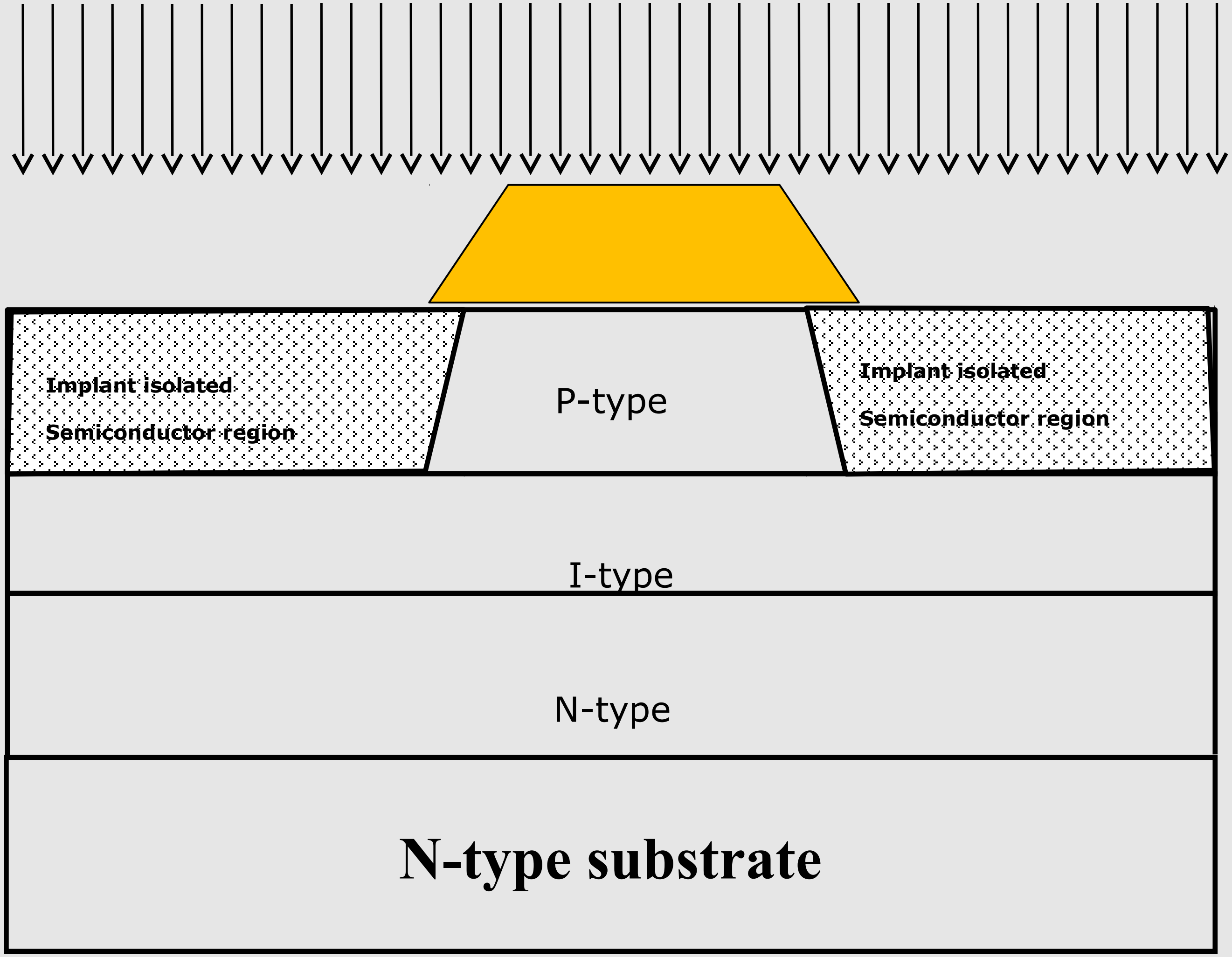
Senior Engineer

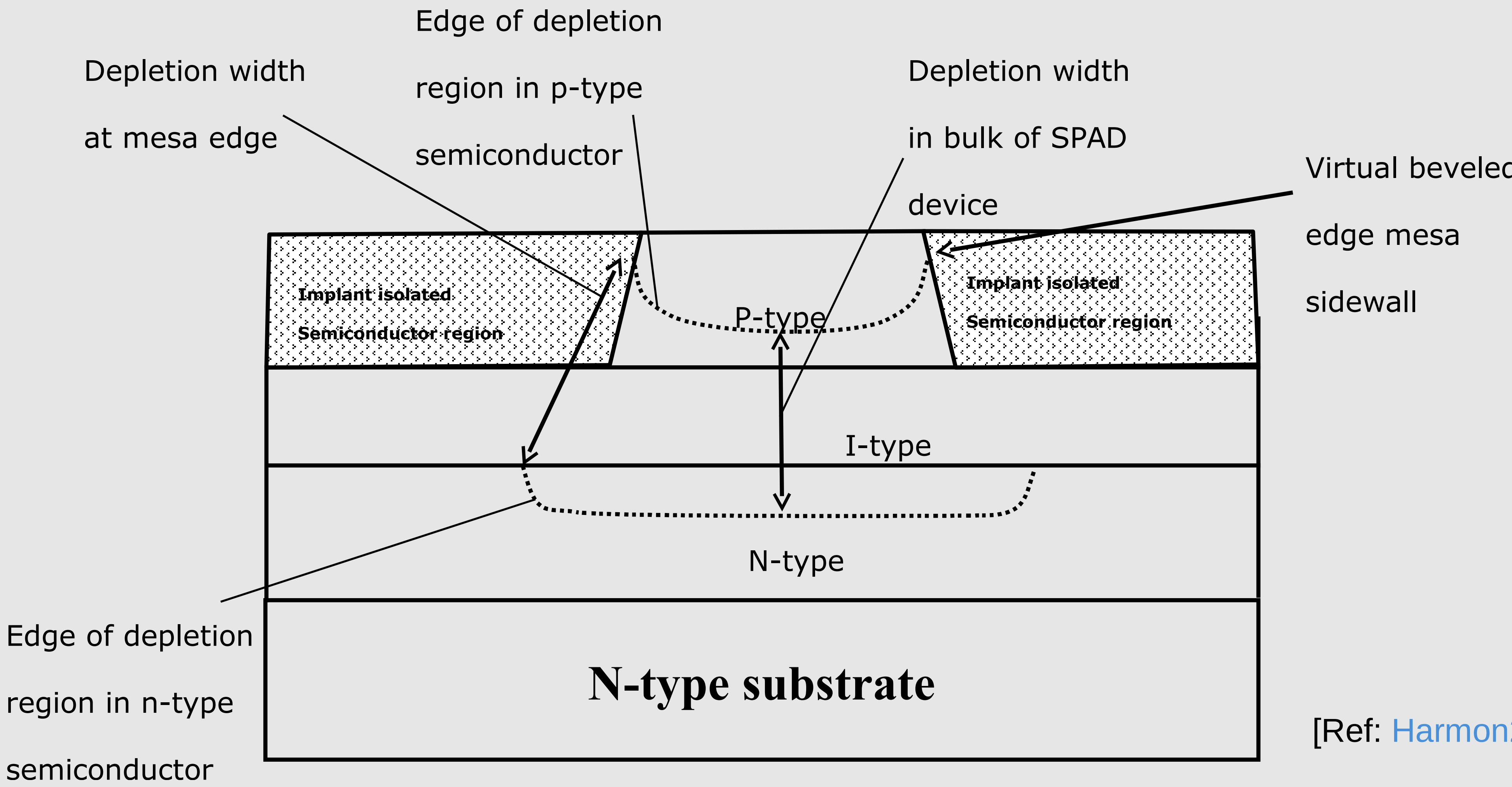
Planar fabrication



[Ref: Harmon2]

- New approach uses implant isolation to form a virtual beveled edge mesa structure.

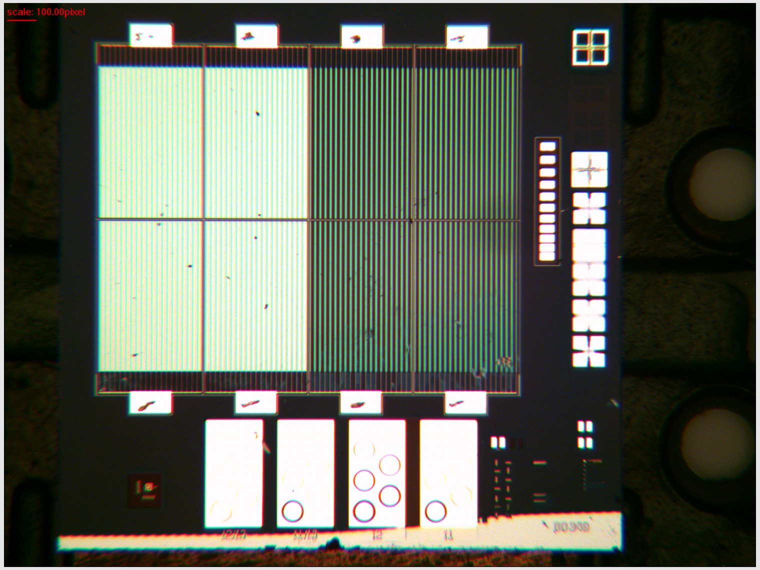
Planar fabrication

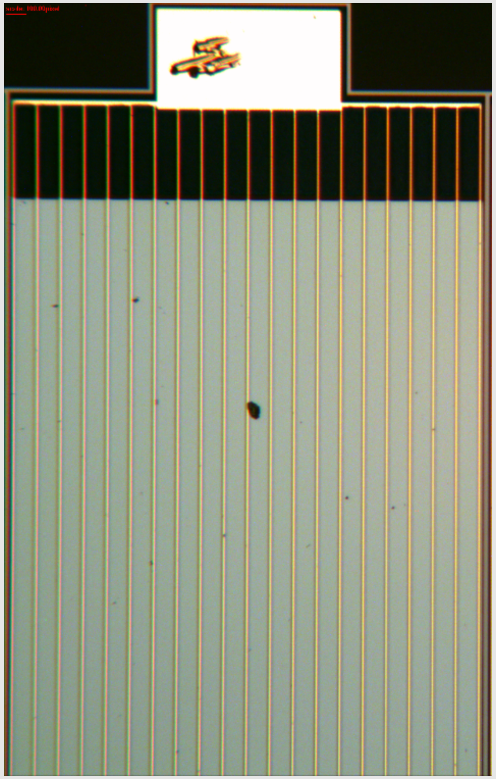


[Ref: Harmon2]

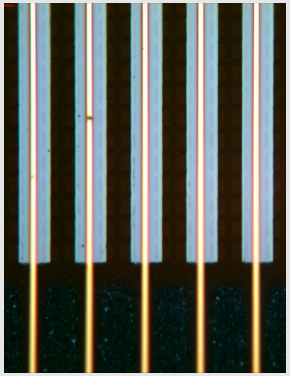
- New approach uses implant isolation to form a virtual beveled edge mesa structure.
- Same approach used for quench resistor (adjustable 100kΩ—1TΩ/□)
- Add trenching to physically separate arrays

Detail views





PMC and
1.0 x 1.5 mm^2
2400 SPAD
25u array

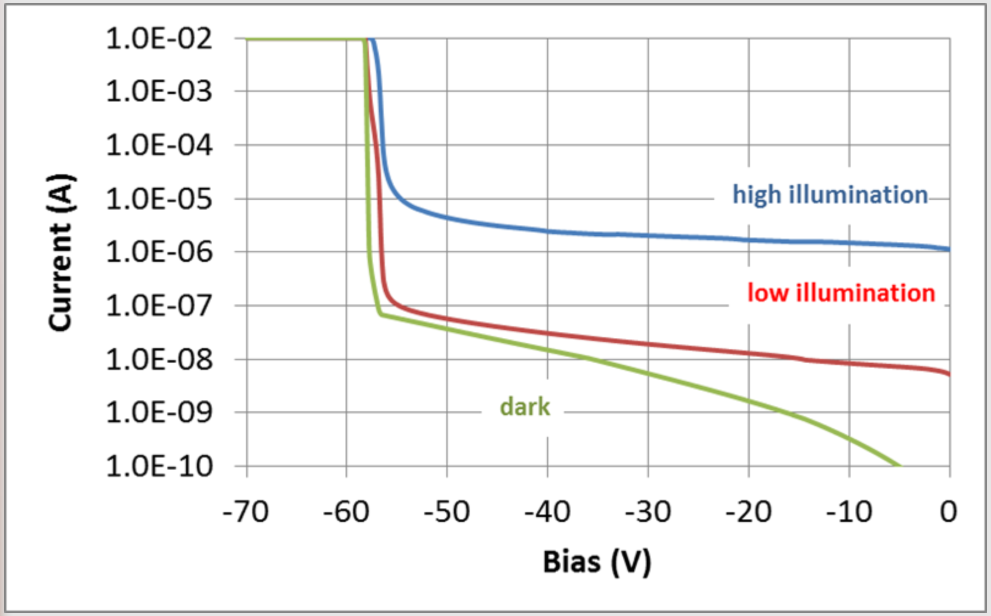


11u pitch device
50 SPADs

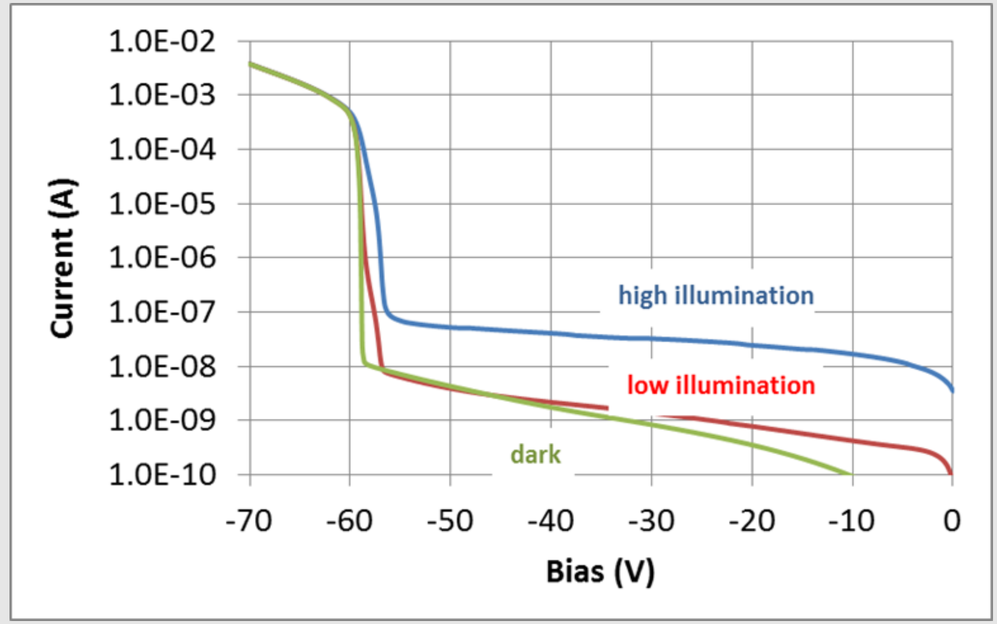
Next: performance characteristics for latest prototype devices

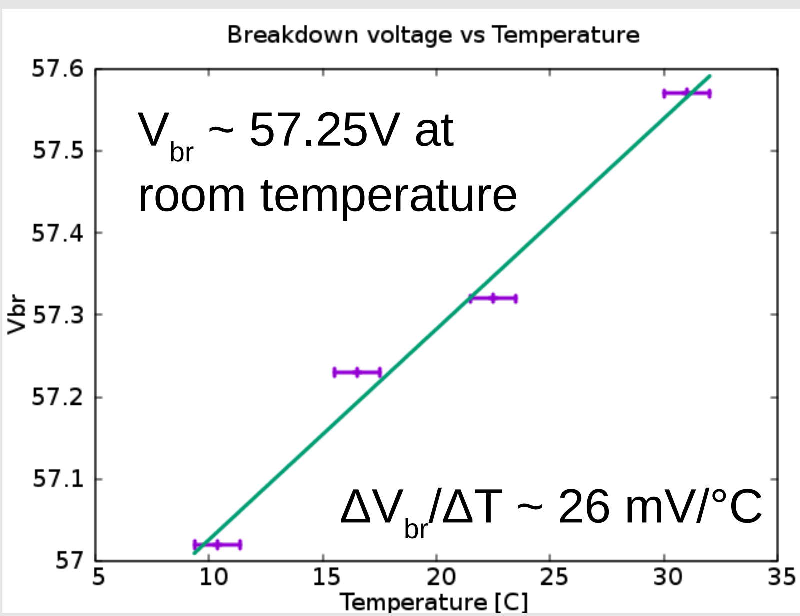
Breakdown characteristics

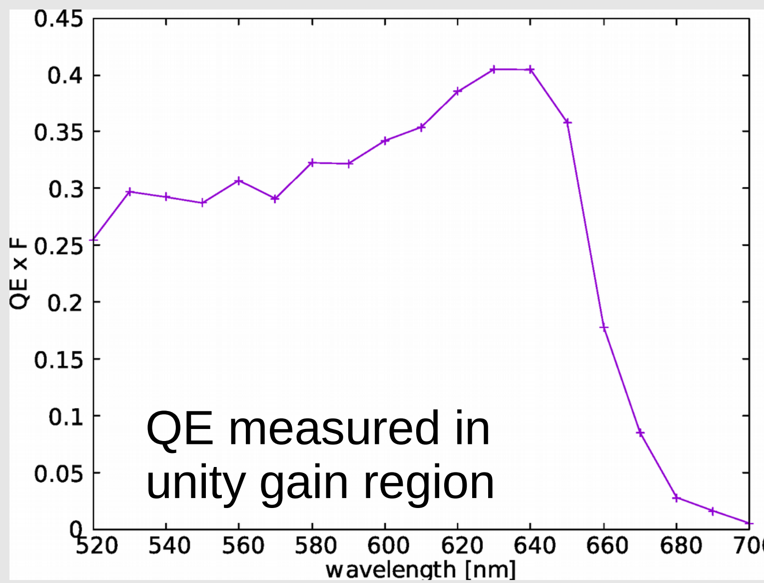
1.0 × 1.5 mm² array
25 µm pitch, 2400 SPADs in parallel



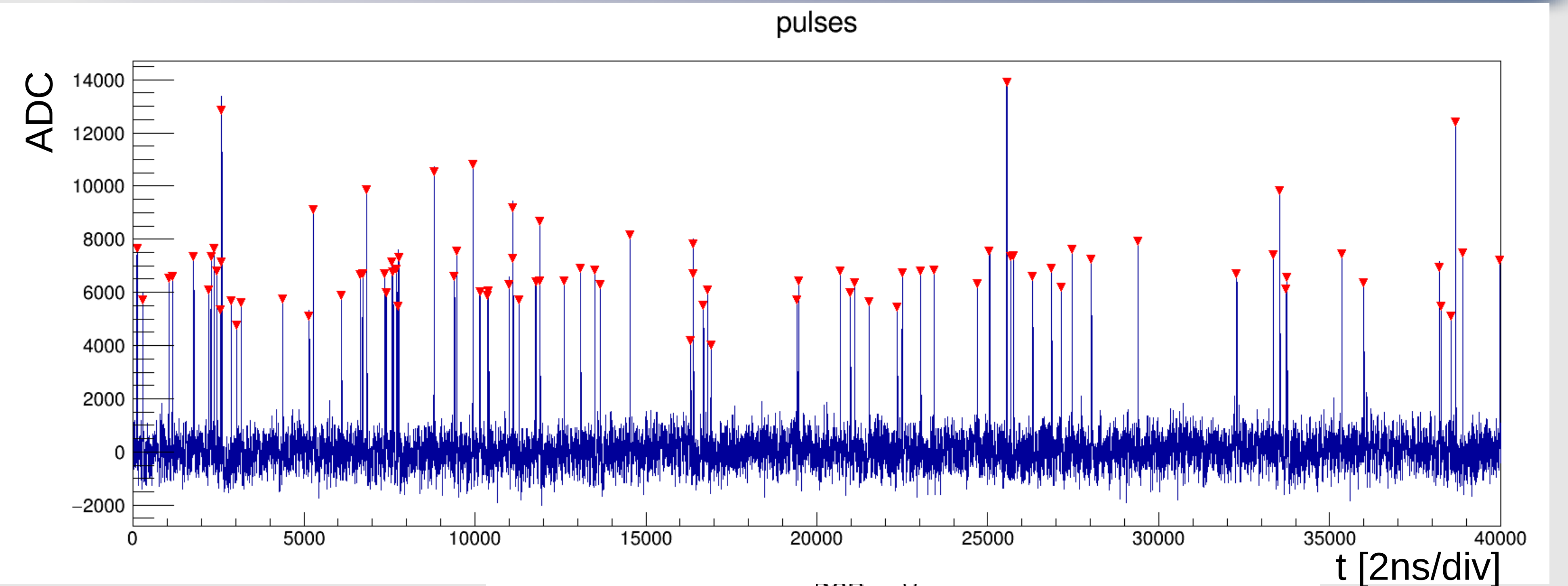
0.05 × 0.1 mm² array
11 µm pitch, 50 SPADs in parallel



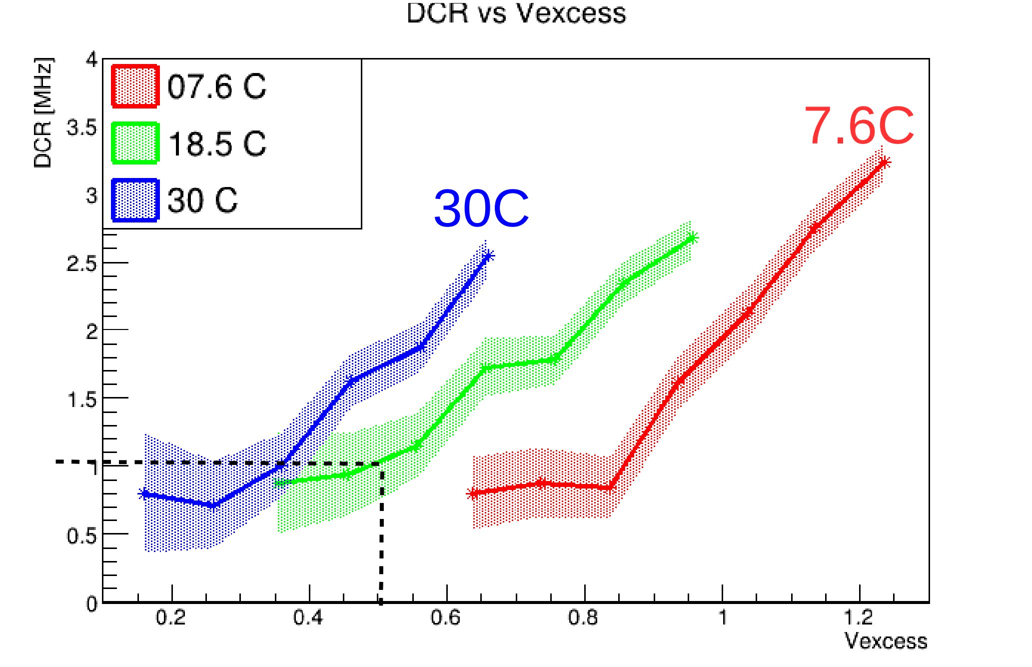




Dark Counts

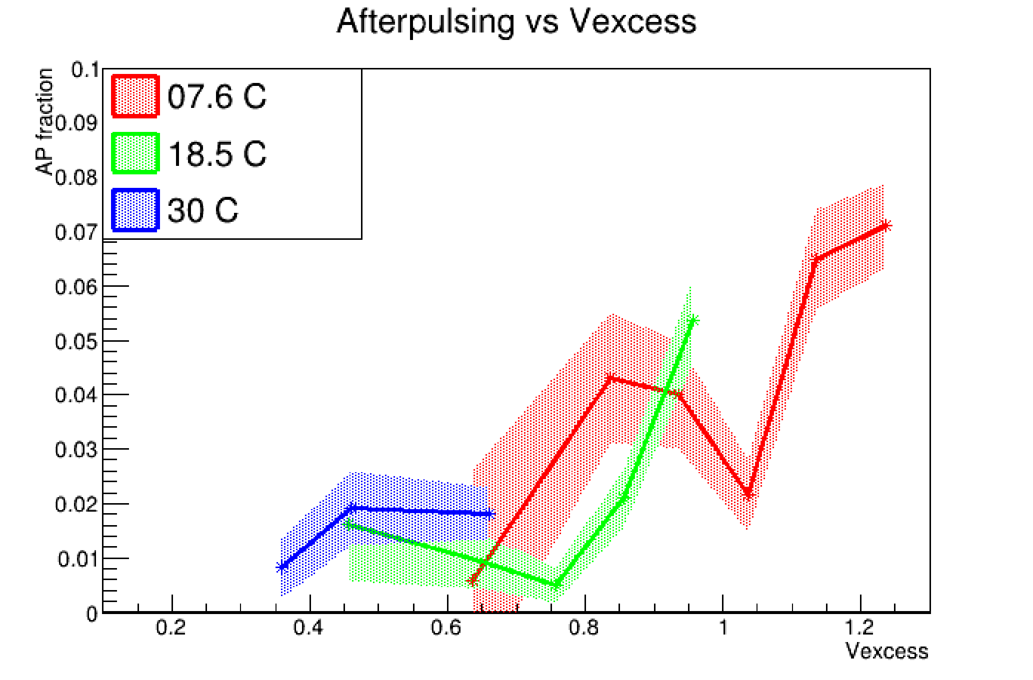


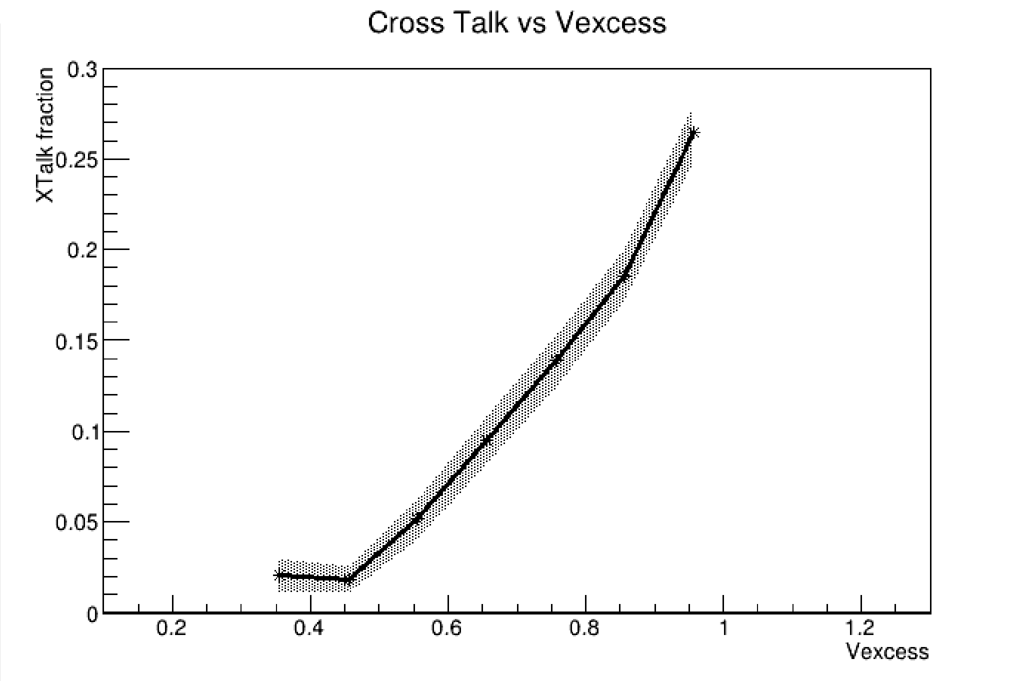
Dark Count Rate vs V_{excess}, T



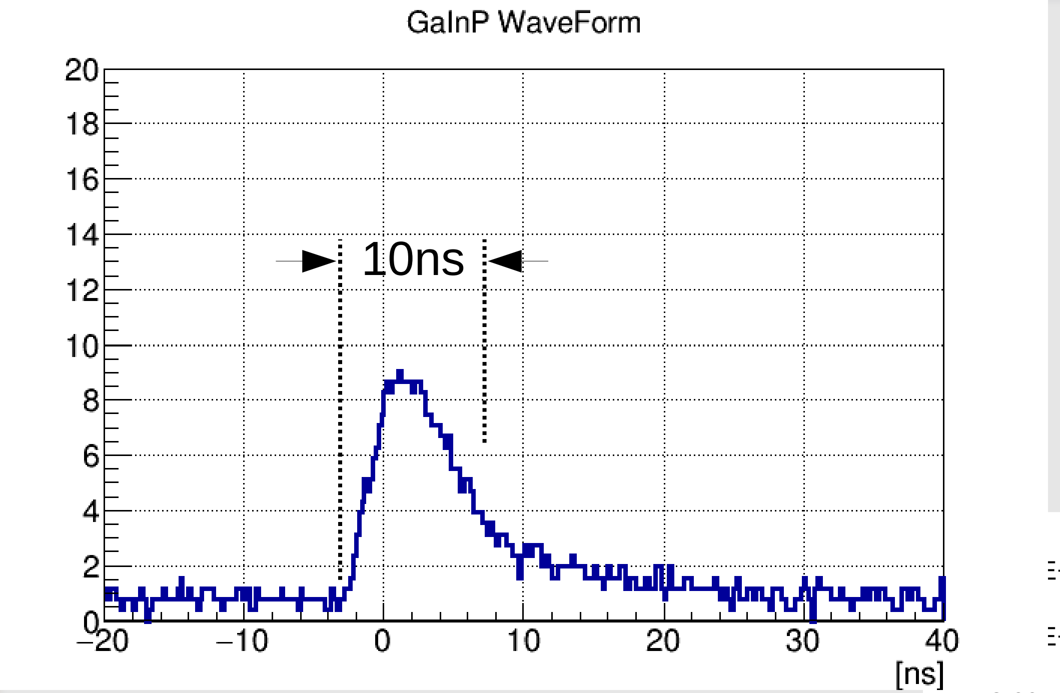
Room temp:
~660 kcps/mm^2
@ Vex=0.5V

Afterpulsing and Crosstalk

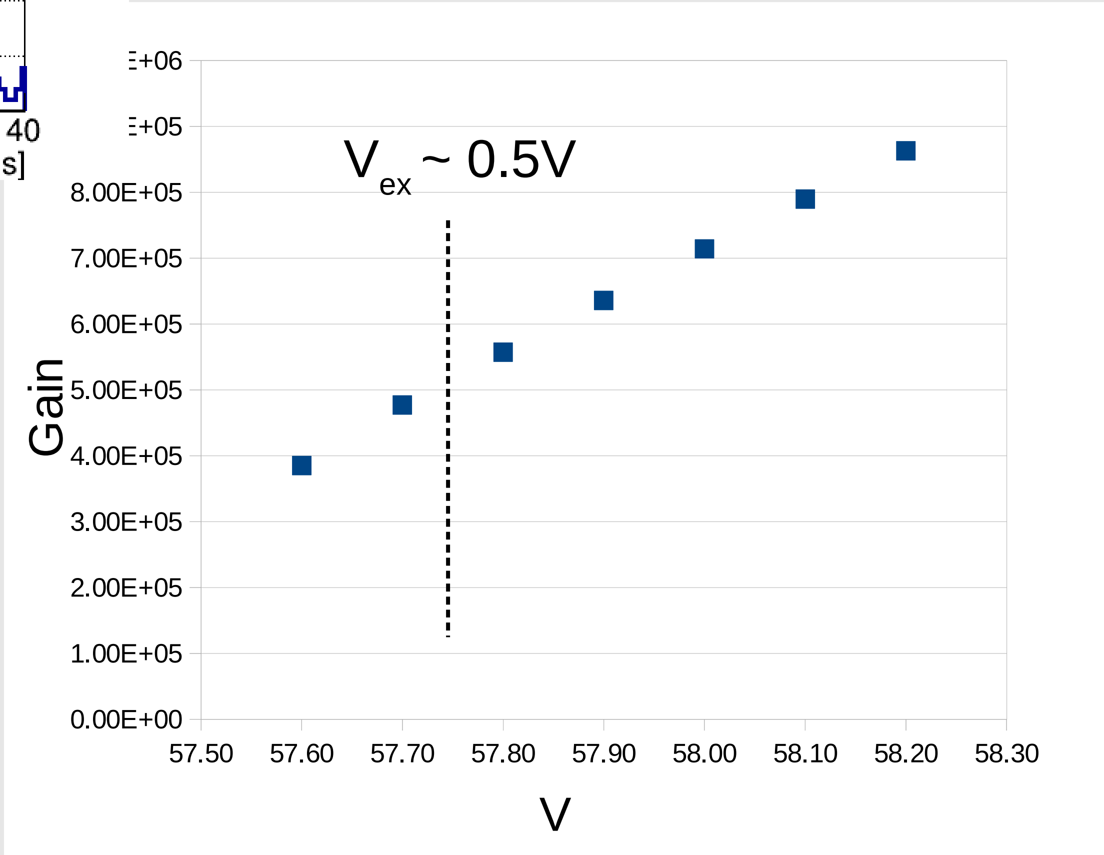




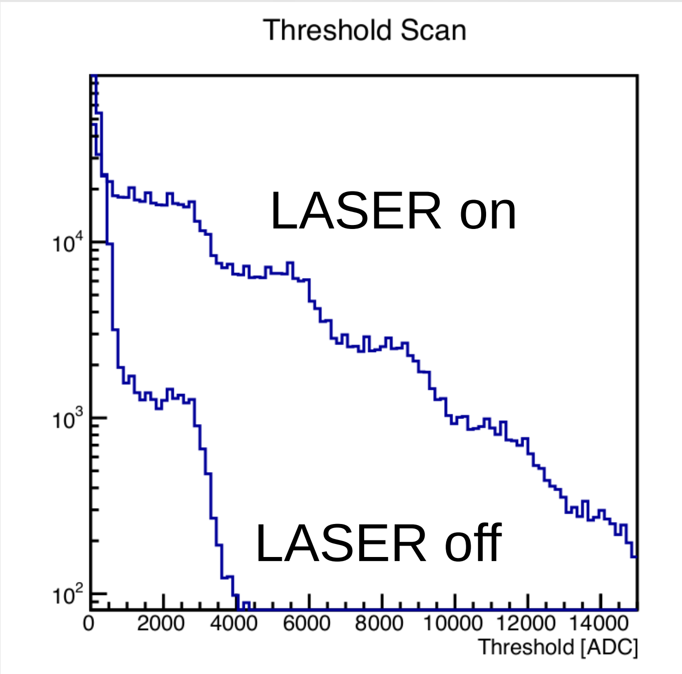
Pulse shape and Gain



Illumination with 520nm LASER
200ps pulsewidth



Multiphoton peak data



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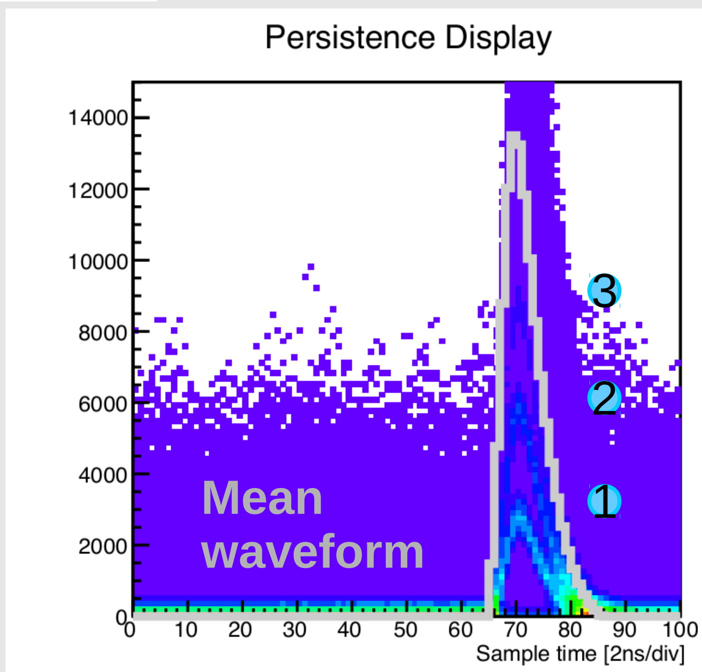
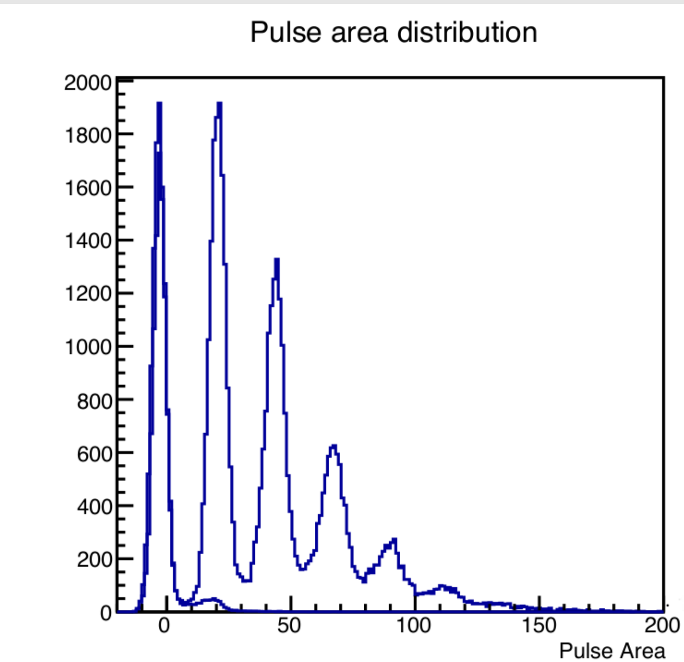




Comments on GaInP PMCs

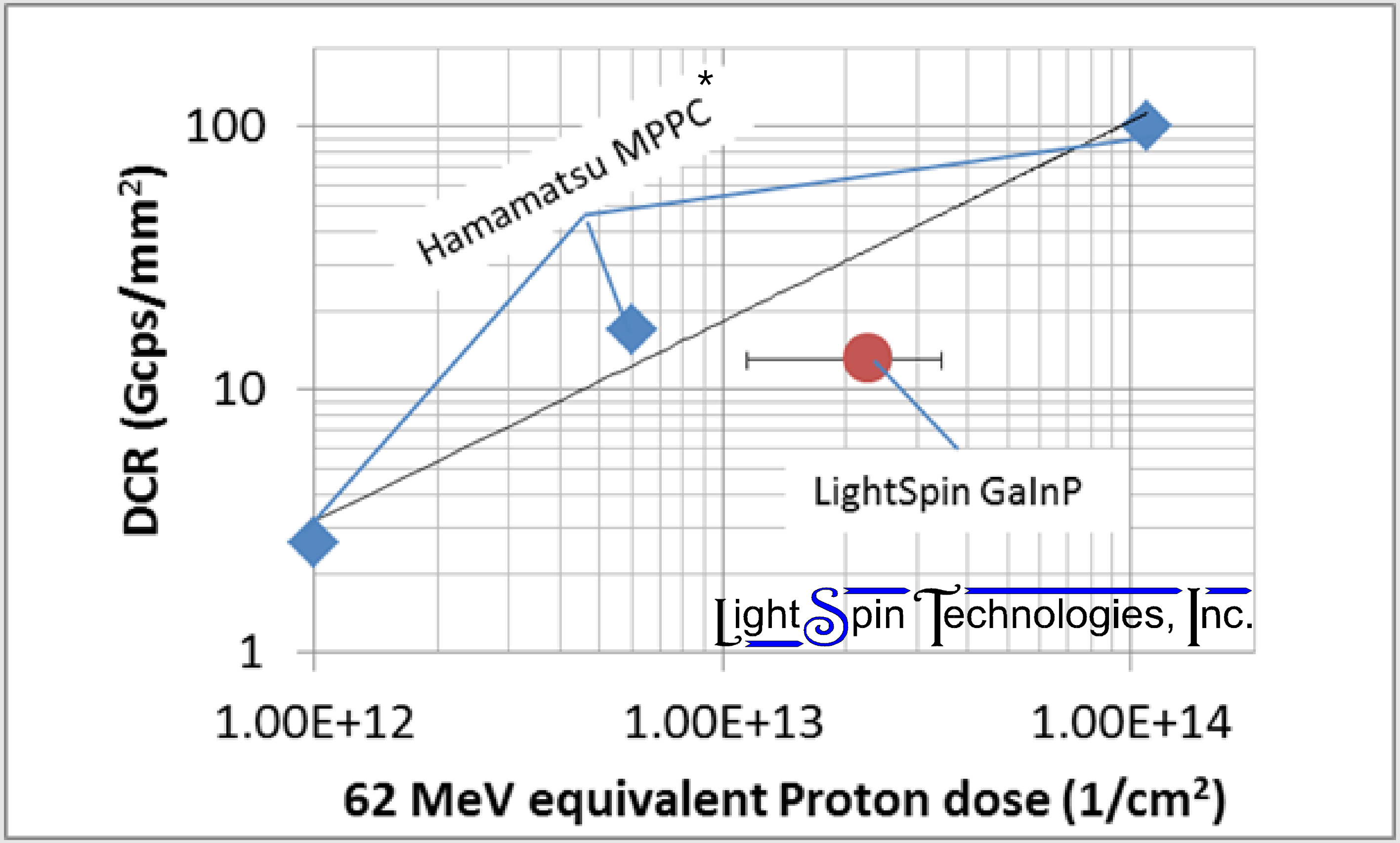
Results shown are for only the latest revision of a 5th generation of test devices.

A variety of epitaxy, structures, surface treatments, Rq implementations have been adjusted over several propotype generations.

Optimizations have incrementally improved DCR, surface leakage current, pulse shape and recovery times, ...

These latest samples provide a first proof of principle that high performance detectors can be constructed using GaInP.

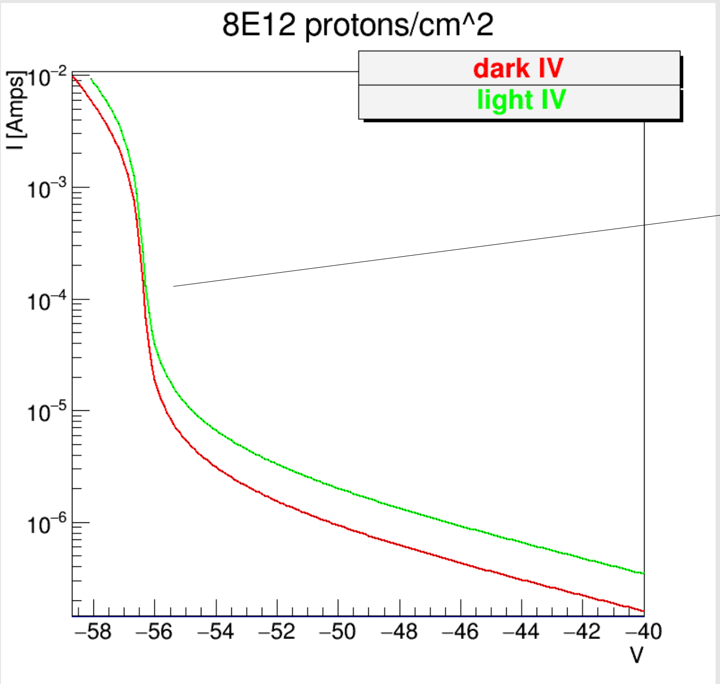
Experimental Radiation Hardness

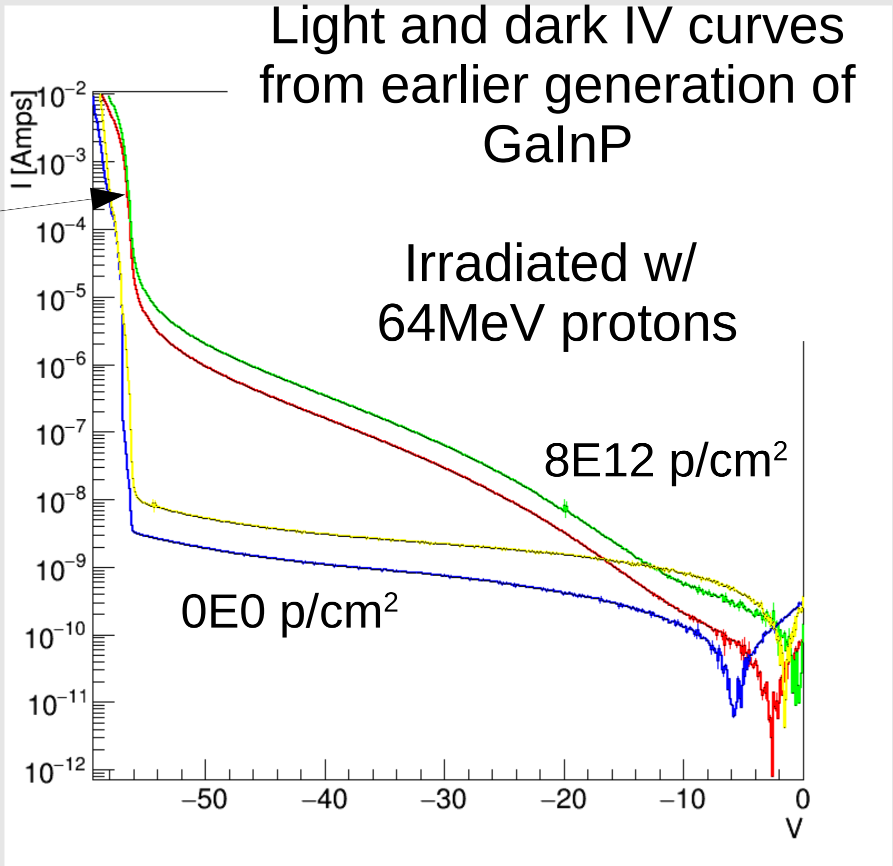


Comparison of effective DCR as a function of 62 MeV equivalent proton dose. Effective DCR is calculated from dark current divided by gain, converted to electrons/second and normalized to 1 mm^2 unit area. Hamamatsu data is from 62 MeV proton irradiation*. LightSpin experimental data is from 180 – 220 keV proton irradiation of GaInP, scaled to 62 MeV.

*Y. Musienko, A. Heering, R. Ruchti, M. Wayne, A. Karneyeu, V. Postoev, "Radiation damage studies of silicon photomultipliers for the CMS HCAL phase I upgrade", NIMA (2015) doi:10.1016/j.nima.2015.01.012

“Qualitative” data from 64 MeV protons



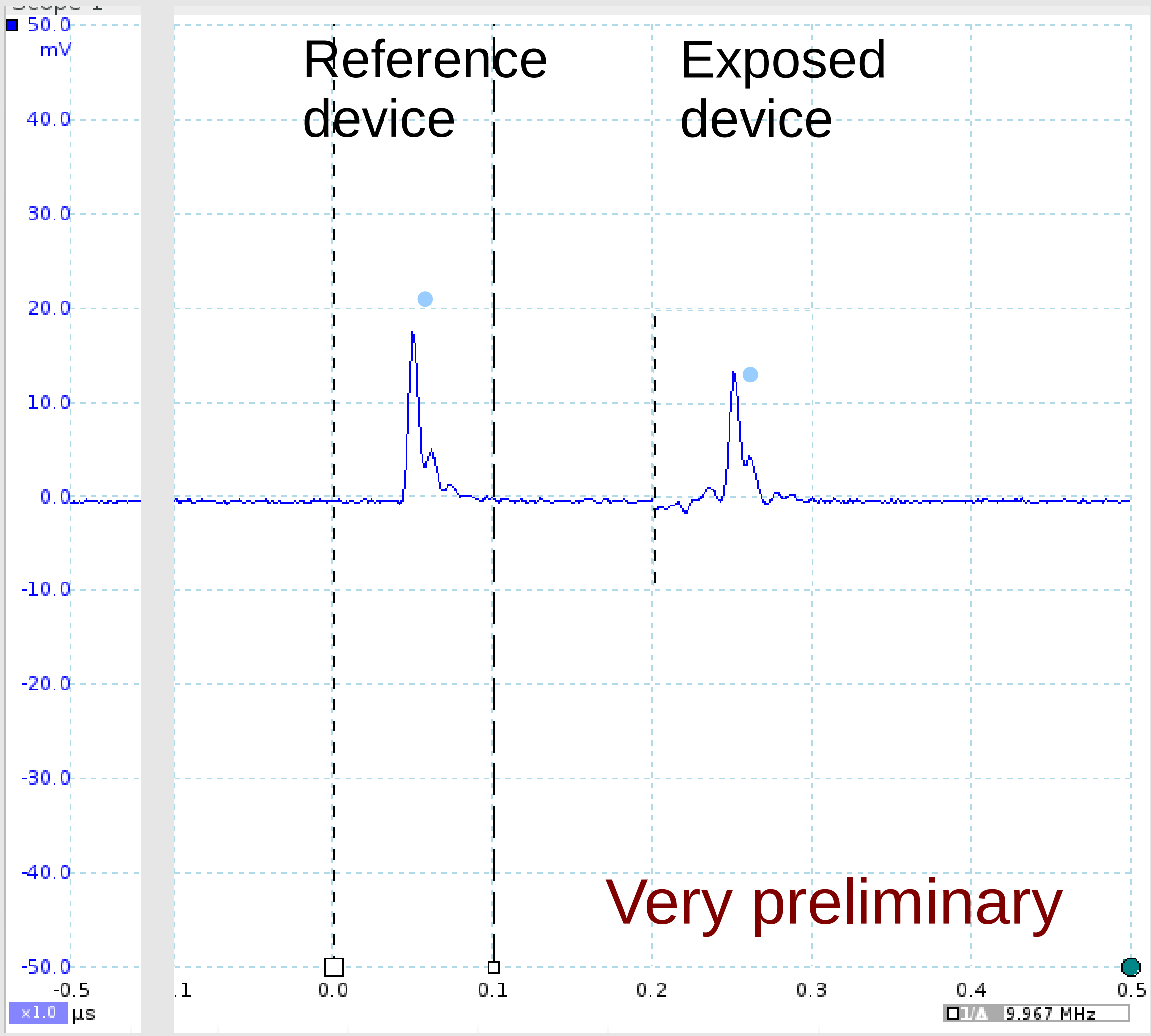


Same epitaxy, but these data a from earlier device tests

Differ from latest devices in:
· Surface treatment
· Larger Rq (longer reset)
· Array isolation (more surface leakage)

Light sensitivity still apparent after exposure

Neutron irradiation at KSU reactor



Response to ~ns laser pulse

Qualitative data only

- Different devices, do not expect equal pulse heights
- Reported exposure as ~4E11, calibrated to 1MeV-N equivalent dose in silicon (wide energy spectrum)
- However, found more than order of magnitude disagreement between calibration and expectations from reactor power… prefer to have alternate reference for calibration.

Summary

SPAD arrays with good photon detection properties can be made using GaInP.
25 and 11 µm pitch demonstrated, ~25 nsec reset time.

GaInP devices are far from fully optimized based on theoretical performance expectations based on theory (band gap, carrier concentration, ...)

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Measured radiation hardness so far "comparable" to silicon. Theory states it should be many orders of magnitude better. Working to understand / speculate on difference:

- Surface passivation: Very likely a problem.
- K value error? Only estimated for GaInP, but unlikely off by many orders of magnitude. SPAD arrays provide an excellent way to measure K-value, and should be able to refine the K value soon.
- Quality of semiconductor?
- Room temperature annealing effect? Silicon likely has better room temperature annealing properties (no antisites).

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New devices currently being fabricated:
- Improved surface preparation, AR coating, better optimized Rq, and electrical contacts.
- Second version with alternate epitaxy process also in preparation.

Processing techniques developed allowing tight pitch arrays (comparable to SiPM) applicable to other semiconductors. GaInP appears to be the best candidate, but additional studies in GaAs, InP, GaN, SiC can be avenues to improve performance and/or wavelength range.

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Expect significantly more data with new, high quality prototypes over the next months.

=> Evaluate prospects for application in High Energy Physics

Additional slides

Figure of merit to compare SPAD performance across materials/device technologies

- $F(\lambda,T_0) = DCR(T_0) / DE(\lambda) / Area$
  - **Result is effective dark count at 100% detection efficiency, normalized to detector area, measured at T_0=300K**
  - Assume $DE(\lambda,T) \approx DE(\lambda)$
    2nd order effects assumed negligible: band gap, after-pulsing, dead time, etc.

- $DCR(T) = C \times DE \times G\text{-}R(T)$
  - C is a constant describing fill factor
  - G-R(T) is the thermal generation rate

- $G\text{-}R(T) \approx (n_i / \tau_{SRH}) \times (Area \times W)$
  - n_i is the intrinsic carrier concentration
  - τ_{SRH} is the thermal generation lifetime
  - W is the thickness of the depletion region
  - Use to estimate τ_{SRH} from DCR

[Ref: Harmon1, Harmon2]

Experimental FOM

$$F(\lambda,T_0) = DCR(T_0) / DE(\lambda) / Area$$

Material	Wavelength (nm)	DCR (Mcps)	Temperature (K)	DE (%)	Area (mm^2)	FOM ($Mcps/mm^2$)
InGaAs	1550	0.040	290	2.8	4.9E-4	2900
Silicon	450	1.6	298	25	36	0.18
GaAs[1]	630	2.0	297	5	0.75	533
GaInP	630	13.2	298	30	1.5	29
4-HSiC	300	1.0	298	8	0.25	50

[1] Harmon, E. S., Naydenkov, M., and Hyland, J. T. "Compound Semiconductor SPAD arrays," Proc. SPIE v. 9113, paper 911305 (2014).

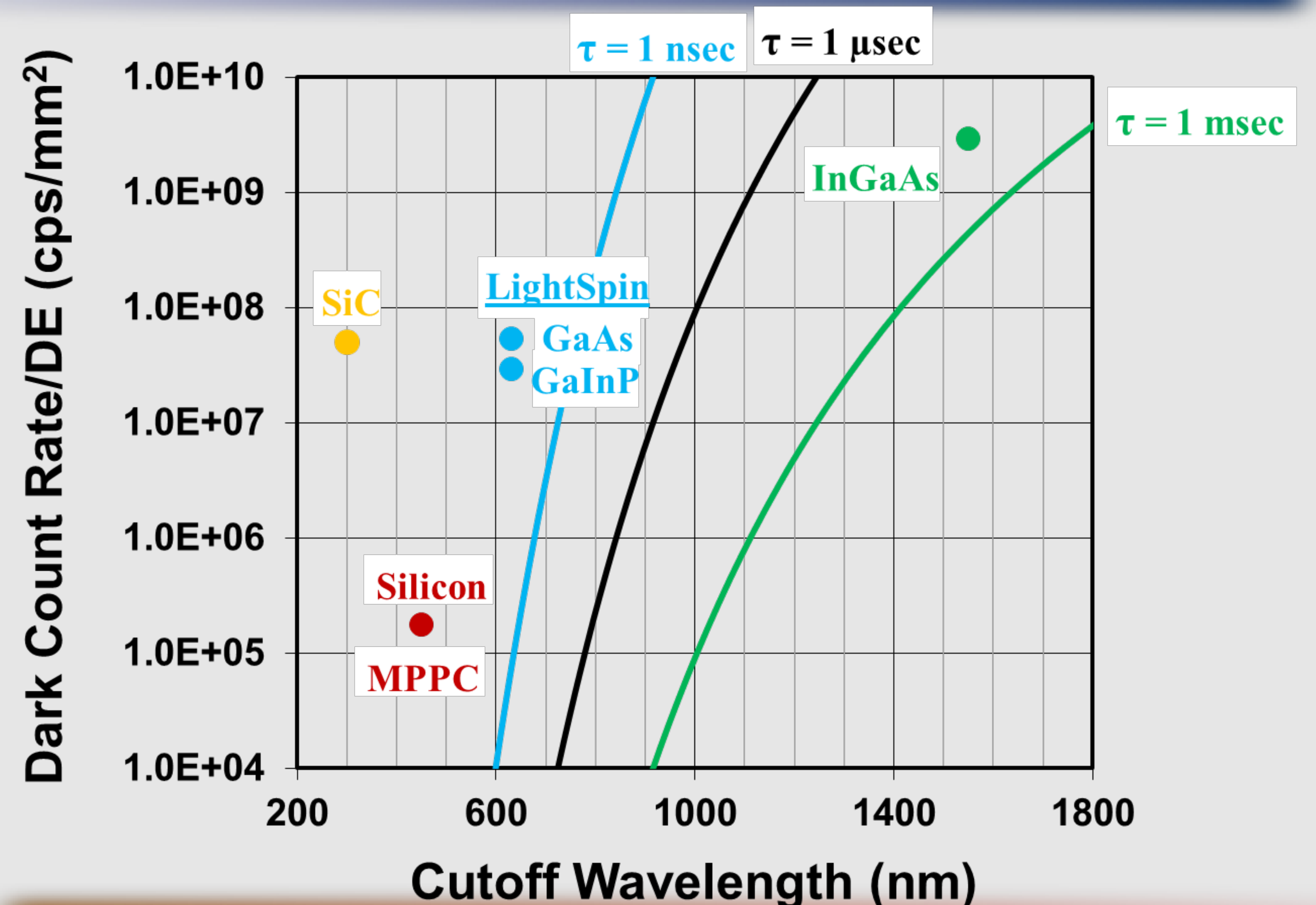
[2] Warburton, R.E., Itzler, M.A., and Buller, G.S., "Improved free-running InGaAs/InP single-photon avalanche diode detectors operating at room temperature", Electronics Letters v. 45(19) Pp. 996 – 997 (2009)

[3] Hamamatsu data sheet MPPC model S13360-6025: http://www.hamamatsu.com/resources/pdf/ssd/mppc_kapd0004e.pdf

[4] Harmon, E. S., Hyland, J. T., Naydenkov, M., "Compound Semiconductor SPAD Arrays," New Developments in Photodetection, Tours, France, July 4, 2014, http://ndip.in2p3.fr/ndip14/AGENDA/AGENDA-by-DAY/Presentations/5Friday/AM/ID34711_Harmon.pdf

[5] Soloviev, S. Dolinsky, S. Palit, S., Zhu, X., and Sandvik, P. "Silicon Carbide Solid-State Photomultiplier for UV light detection", Proc. SPIE v 9113, paper 911305 (2014)

FOM for state-of-the-art



State-of-the-art and theory

Material	FOM Mcps/ mm^2	Temperature (K)	$n_i(T)$	τ	Available improvement	Comment
InGaAs	2900	290	5.2e11	180 μsec	< 10×	Already optimized
Silicon	0.18	298	7.4e9	42 msec	< 10×	Already optimized
GaAs	533	297	1.9e6	3.6 nsec	> 10×	Some improvement available
GaInP	29	298	210	7 psec	> 10,000×	Significant optimization available
SiC	50	298	6e-9	1e-22 sec	>1E10	Unphysical τ – dominated by surface effects?

- Silicon (MPPC) has best FOM
- But, semiconductors with band gap > 1.5 eV should be better. Why not demonstrated?
  - Low quality semiconductors … τ < 1 nsec
  - Perimeter generation → surface defects
  - After pulsing
  - ~~Tunneling?~~
- Silicon/InGaAs close to ideal
- GaAs good (τ = 3.9 nsec)
- GaInP/SiC have tremendous room for improvement
- Theory provides basis for analysis

Summary

- FOM: Dark count rate at 100% detection efficiency, 300K
  - DCR/DE gives the estimated dark count rate at 100% DE
  - Scale by $n_i(300K) / n_i(T)$ to adjust for measurement temperature
  - Measure of materials quality/device maturity
- Planar GaInP Photomultiplier Chips™
  - 11 µm pitch demonstrated
  - 25 nsec reset time
  - 4% DE @ 4 Mcps/mm^2 ➔ FOM = 100 Mcps/mm^2
  - Measured devices exhibit high dark count rates compared to theory:
    - Effective Thermal Generation rate is 3 psec?
    - Significant room for improvement … nsec to µsec feasible
  - 10 – 20% optical cross talk in 25 µm pitch
  - After-pulsing Rate 10% for 25 nsec